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THE OXIDATION, IGNITION, AND DETONATION OF
FUEL VAPORS AND GASES

XV. THE CONCENTRATION OF FINELY DIVIDED CARBON IN TOWN GAS-AIR
MIXTURES REQUIRED TO INDUCE SEVERE KNOCKING COMBUSTION

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THE OXIDATION, IGNITION, AND DETONATION OF FUEL VAPORS AND GASES

XV. THE CONCENTRATION OF FINELY DIVIDED CARBON IN TOWN GAS-AIR MIXTURES REQUIRED TO INDUCE SEVERE KNOCKING COMBUSTION¹

BY R. O. KING², E. J. DURAND³, AND A. B. ALLAN⁴

Abstract

When using gaseous fuels for the C.F.R. engine, the lubricating oil decomposed to finely divided carbon when the gas was hydrogen and optimum spark advance nearly zero. When town gas was used, optimum spark advance varied from 85 to 15 degrees of crank angle, according to mixture strength, and the lubricant yielded carbon of the hard adherent graphitic variety. When using an L head engine having a combustion chamber with a large surface-to-volume ratio and with the spark plug so placed that optimum spark advance for town gas was approximately half that required with the C.F.R. engine, no appreciable carbon deposit of any variety was obtained. Conditions were therefore such that knocking combustion observed on adding finely divided carbon to the gas-air mixture was not caused to any appreciable degree by carbon derived from the lubricant. It was then found on adding carbon, as graphite dust, at a measured rate to the entering mixture, that approximately 0.3 mgm. in the end gas caused a knock intensity of the degree required to reduce brake horsepower by from 10 to 14%.

Introduction

The experiments described in this Part were made in the course of an investigation of the factors which have hitherto prevented the use of fuel gases in Otto cycle spark ignition engines at other than economically low compression ratios. The experiments deal especially with nuclear ignition which is of interest in respect of the ignition and explosion, in any circumstances, of mixtures of air with combustible gases or vapors.

The investigation was begun with hydrogen and experiments, Part V (4), demonstrated that the gas could be used in any proportion in mixtures with air at a compression ratio as high as 10 : 1 if it were not impregnated with finely divided carbon derived from pyrolysis of the lubricating oil. It was expected, therefore, that finely divided carbon would be formed when town gas containing hydrogen in a concentration of nearly 50% was used in the engine and that consequent nuclear ignition would again be obtained. It was found, however, as a result of experiments made accordingly and described in Parts XII (2) and XIII (3), that the carbon residue in the combustion chamber was of the hard and adherent graphitic type. There was little if any evidence of the finely divided variety having been formed and a compression ratio of 12 : 1 was used without the occurrence of nuclear ignition.

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The further experiments described in this Part were made with the Armstrong-Whitworth knock testing engine (1) and the results differed from those obtained with the C.F.R. engine in that no appreciable amount of carbon of any variety remained in the combustion chamber.

The experimental results are interpreted as showing why the oil used to lubricate the pistons of internal combustion engines may or may not leave a carbonaceous deposit in the combustion chamber and why a deposit may be of the finely divided or the adherent graphitic type.

The conditions in which the lubricating oil left no carbon in the combustion space having been ascertained, it became possible on adding finely divided carbon to the gas-air mixture at a measured rate to determine the concentration required to cause nuclear ignition and consequent combustion knock of the intensity required to reduce power by a measurable amount.

Experimental Arrangements and Methods

The Engine

A desirable feature of the Armstrong-Whitworth engine is that the detachable head facilitates the inspection or removal of carbonaceous or other deposits that may have collected in the combustion chamber or adhered to the surfaces. The disadvantages of the engine are that the maximum designed compression ratio is 8:1 only and that the attainable mean effective pressure is low as compared with that of the C.F.R. engine.

The essential features of the combustion chamber are illustrated by Fig. 1. The plunger *P* is adjustable by a screw to vary compression ratio over the

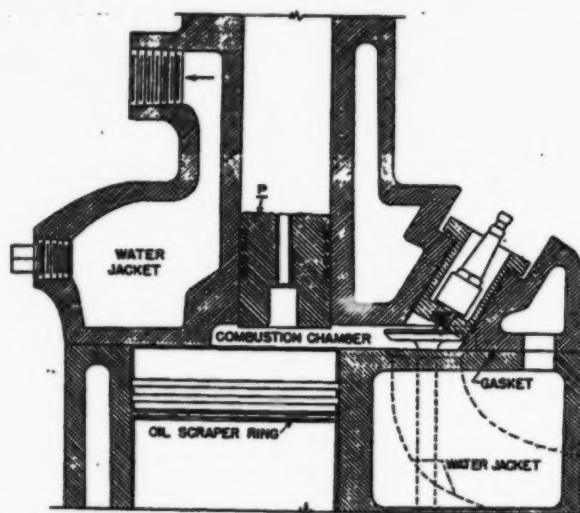


FIG. 1. Combustion chamber arrangements—Armstrong-Whitworth engine.

range 4 to 8 : 1. The higher value of 9 : 1 used for the experiments presently described was obtained by lowering the plunger to project $\frac{1}{8}$ in. into the combustion space, by reducing the volume of the spark plug hole, and by using an extra-thin, $\frac{1}{64}$ in. asbestos composition cylinder head gasket.

The cylinder diameter is $2\frac{3}{8}$ in., the stroke $3\frac{1}{2}$ in., and the stroke volume 22.7 cu. in. The engine and a direct connected swinging field electric dynamometer are mounted as a unit on a cast iron bedplate. The engine was designed originally for the knock rating of fuels but became obsolete on the universal adoption of the C.F.R. engine for that purpose.

Lubrication and Carbon Deposits

It was necessary for the experiments that excess lubricating oil should not pass the piston and that the cylinder head gasket should be tight enough to prevent water or steam entering the combustion space. Some difficulty was experienced in overcoming the evils. The oil difficulty disappeared on replacing the lowest of the three pressure rings by an effective scraper ring fitted in a groove widened from 0.125 in. to 0.140 in. to receive it and on replacing the remaining pressure rings by new ones of a superior design. Water leakage was stopped, in spite of the extremely thin gasket, by scraping the surfaces of the cylinder head and block to an approximate surface plate flatness.

Method of Admitting Finely Divided Carbon, as Graphite Dust

Mechanical methods were tried, beginning with a screw feed stoker design as mentioned in Part V (4). All were defective for the principal reason that induction oscillations made it difficult to govern the rate of feed by mechanical means. It was decided finally to make use of the oscillations to assist in picking up and feeding the dust into the combustion chamber. The device

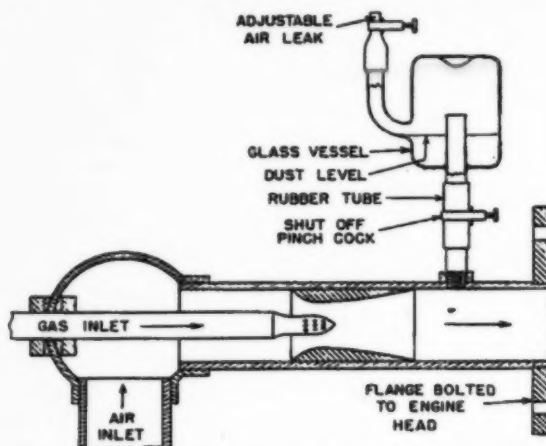


FIG. 2. Device for adding graphite dust to the gas-air mixture.

used was fitted to the induction pipe between the carburetor and the engine head as illustrated by Fig. 2. It comprises a glass vessel with a central standpipe for the admission of the oscillations from the induction pipe and a filling tube at one side. The device is set in operation by fully opening the lower pinchcock, and the rate at which dust is picked up and carried into the combustion chamber can be varied by adjusting the pinchcock at the top of the side tube to provide a small air leak. The vessel is filled with dust to the level shown by the illustration before taking an observation, and the air oscillations act to remove dust at a rate depending on the size of the air leak. The rate is substantially uniform if not more than a total depth of about $\frac{1}{8}$ in. of dust is removed before refilling. The vessel can be refilled without altering the size of the air leak. The regularity of the action is no doubt due to the magnitude of the oscillation remaining constant when the engine speed is unchanged, and the mixture supplied at constant pressure, no throttle being used.

Particulars of Toronto Town Gas

Analysis of Toronto town gas is carried on continuously by the Consumers' Gas Company. The composition determined at the time of the experiments is given below,—

TABLE I
COMPOSITION OF TORONTO TOWN GAS

Constituents	Percentage volume
Hydrogen	47.5
Carbon monoxide	21.3
Methane	12.3
Nitrogen	7.8
Carbon dioxide	4.6
Ethylene	3.9
Ethane	1.1
Benzene	1.0
Oxygen	0.5

The gas contains a trace of organic sulphur not exceeding 10 to 15 grains per 100 cu. ft.

Hydrocarbons constitute a relatively small proportion of the gas and with the exception of the ethylene present in very small concentration are of the type to resist pyrolysis to finely divided carbon even at the temperature of the end gas, that is, they are of the nonknocking variety.

The higher calorific value determined by calorimeter in the Gas Company Laboratory was 467 B.t.u. per cu. ft. at 60° F. and 30 in. of mercury. The lower value, by calculation, was 424 B.T.U. per cubic foot and the density 0.0409 lb. per cubic foot.

The rate of gas supply to the engine was measured by a standard dry meter fitted with a special dial for accurate reading and calibrated by the Consumers' Gas Company.

Experimental Results

Performance Data for the Armstrong-Whitworth (A-W) and C.F.R. engines

Performance data for the two engines were obtained by trials in like conditions for the purpose of facilitating comparison of later experimental results. The trial conditions were, speed 800 r.p.m., jacket coolant 212° F., air and gas at laboratory temperature, and compression ratio 9 : 1.

The value assigned to the compression ratio is based on a measurement of the clearance volume, but even if measurement be correct the *compression pressure* will be less than the correct corresponding value to an extent depending mainly on the amount of leakage past the piston, valves, and cylinder head gasket. The maximum compression pressure for the A-W engine in the conditions mentioned above, taken immediately after running under power, was 207.5 lb. per sq. in. when atmospheric temperature was 85.8° F. and pressure 29.69 in. of mercury. The comparable compression pressure

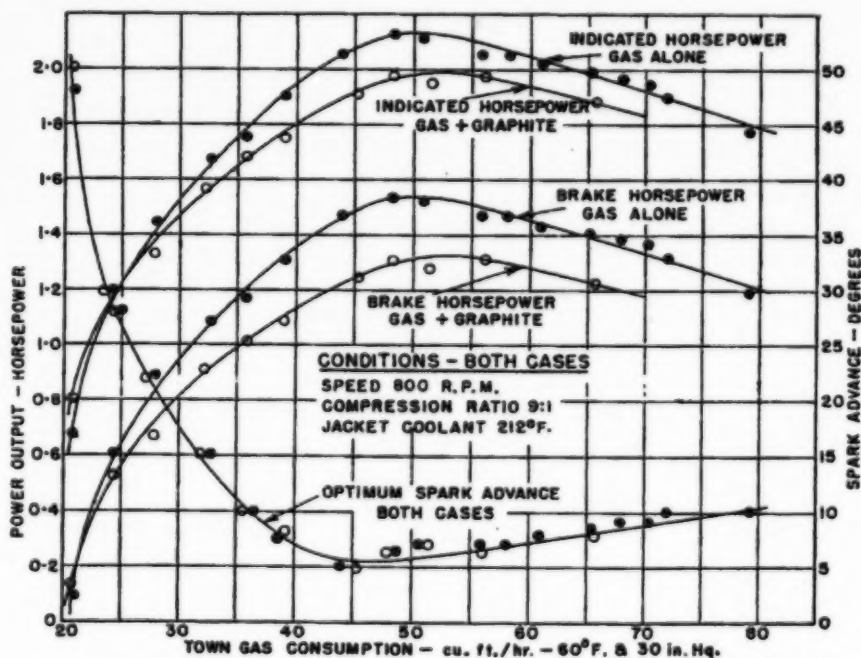


FIG. 3. A-W engine trial results showing variation of optimum spark advance with mixture strength and the reduction of brake and indicated horsepower due to severe knocking combustion induced by graphite dust.

for the C.F.R. engine was 209.0 lb. per sq. in. when atmospheric temperature was 82.5 °F. and pressure 29.8 in. of mercury. The small difference of 1.5 lb. per sq. in. in favor of the C.F.R. engine can be accounted for in part by the lower atmospheric temperature and higher pressure and in part by the piston being fitted with three pressure rings instead of the two of the A-W engine. Moreover, there is always a possibility of leakage past the cylinder head gasket of that engine, whereas the C.F.R. engine is constructed with the cylinder head and barrel in one piece, and a jointing gasket is not required.

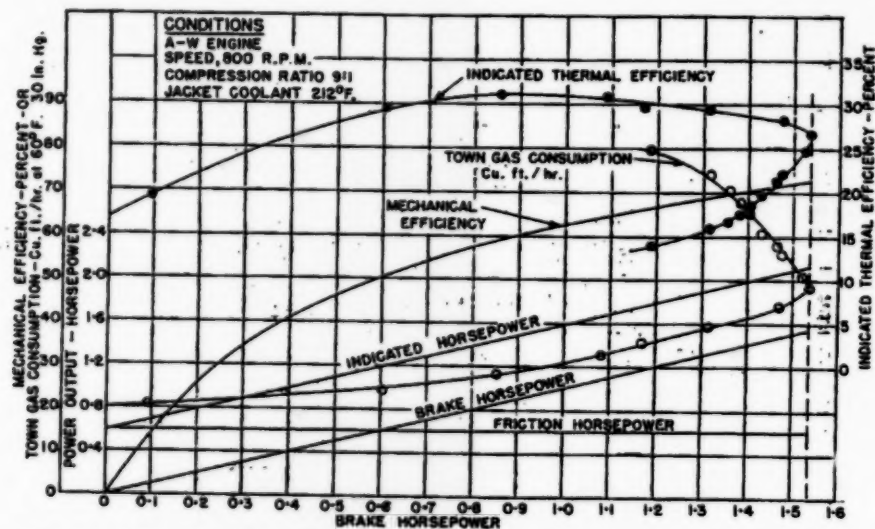


FIG. 4. A-W engine trial; collected results showing especially that indicated thermal efficiency reaches a maximum at 55% of full load and then diminishes as mixture strength is weakened to reduce power.

Performance data for the A-W engine are given in some detail by the graphs of Figs. 3 and 4. The similar data for the C.F.R. engine need not be given in detail, the essential difference between the performances of the two engines being shown by the graphs of Fig. 5. They show that indicated mean effective pressure for the C.F.R. engine attained a value of 120 lb. per sq. in., the corresponding indicated thermal efficiency being 33%. The similar values for the A-W engine were 92 lb. per sq. in. and 27%. The indicated thermal efficiencies attained at the mixture strengths for maximum economy were 39.5% for the C.F.R. and 31.0% for the A-W engine.

The inferior performance of the A-W engine is attributed, in accordance with experiments made by Ricardo (6, p. 203), to the relatively large surface-to-volume ratio of the combustion chamber. The ratio is usually calculated on the basis of the piston being at top dead center. The effective ratio is however that calculated for the position of the piston when combustion is

appreciable. That would be at about 10 crankshaft degrees after passage of the spark. On this basis the surface-to-volume ratio is 7.6 for the A-W and 3.1 for the C.F.R. engine, the ratios being taken for piston positions at maximum thermal efficiency when spark advance is 50° for the C.F.R. and 32° for the A-W engine.

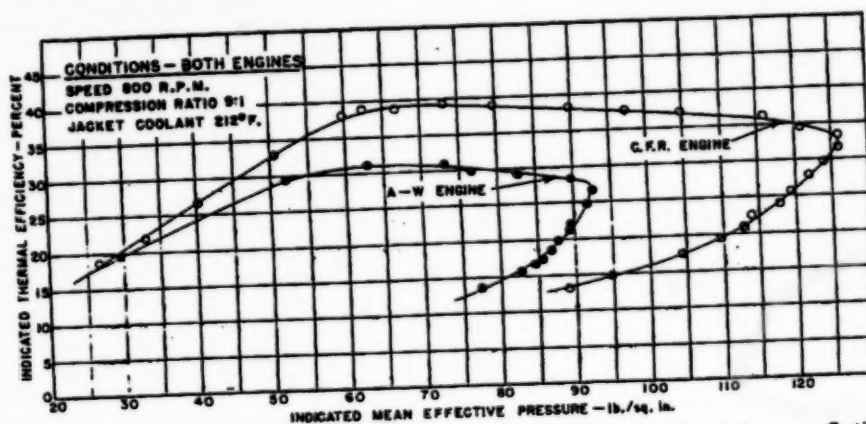


FIG. 5. Relative performances in terms of indicated thermal efficiencies and mean effective pressures of the C.F.R. overhead valve engine and the A-W, L head side valve engine.

- Spark Plug Position and Optimum Ignition Timing

Optimum ignition timing varies with mixture strength and was determined by a separate series of experiments as described in Part XII (2, p. 438). The values so obtained for the A-W engine as given graphically, Fig. 3, are much less than values obtained similarly for the C.F.R. engine. At maximum power, optimum ignition timing required a spark advance of 7° for the A-W and 15° for the C.F.R. engine. At minimum power, zero brake horsepower, optimum ignition timing for the A-W was 50° spark advance and 85° for the C.F.R. engine. The somewhat remarkable difference is attributed to the difference in spark plug position. The spark plug of the A-W engine is situated between the side-by-side inlet and exhaust valves and close to them. Thus the spark passes and flame propagation begins in what is substantially freshly admitted combustible mixture that has been heated by contact with the exhaust valve as well as by compression. The spark plug of the C.F.R. engine is situated as far as space permits from the inlet and exhaust valves which are as widely separated as space permits. Thus on the passage of the spark, flame propagation must occur in a mixture diluted to the maximum possible extent with residual exhaust gas, consequently an unusually large advance is required for optimum ignition timing, especially when weak mixtures are used. The attainment of 100% quality control when using the standard ignition system is attributed to the advantageous position of the spark plug.

Combustion Chamber Cleanliness

It was of importance to determine if the experimental arrangements were effective to prevent the accumulation of loose carbon in the combustion space. A trial was run accordingly at maximum power for a period of 92 hr., not continuously. The lubricant was composed of commercial acid-refined hydrocarbon oils blended in the laboratory to provide an S.A.E. 30, viscosity grade. The engine ran for the period without developing combustion knock, and occasional inspection made after removing the engine head showed that carbon was not accumulating in the combustion chamber. At the end of the 92 hr. running time there was a trace only of adherent carbon as a narrow ring around the periphery of the piston and a corresponding faint ring of adherent carbon on the flat part of the head adjacent to it at top dead center. The faint ring of carbon was no doubt due to oil thrown from the edge of the piston as the motion reversed at top dead center. There was also a slight deposit of adherent carbon adjacent to the inlet valve. Otherwise the chamber was clean.

Rate of Admission of Graphite Dust and Consequent Knock Intensity

Graphite instead of carbon dust was used for the experiments, in the expectation, based on earlier experiments, that it would be the more likely to remain dispersed in the gaseous mixture instead of clinging to surfaces and accumulating in the combustion chamber.

The graphite dust, grade No. 2301, was supplied by the Canadian National Carbon Company Limited and consisted of a mixture of "impalpable" powder and larger particles that had passed through a 200 mesh to the inch sieve. The grade is that commonly used in iron foundries for dusting on green sand molds.

Knock intensity is a relative term and the C.F.R.-A.S.T.M. method of defining it in terms of the Octane Scale is unsuitable for use with a non-knocking fuel such as town gas, and a practicable method seemed to be to admit the graphite dust at a constant rate and to determine the consequent degree of knocking combustion in terms of the resulting drop in power and thermal efficiency. What can be described in general terms as steady severely hard knock was obtained when the graphite dust was admitted at the rate of 1.3 oz. per hr. which at the engine speed of 800 r.p.m. is 1.5 mgm. per induction stroke.

The engine performance in terms of brake and indicated horsepower is shown by the graphs of Fig. 3 for gas alone and for gas plus graphite dust admitted at the rate mentioned. The severe knocking combustion induced on adding the dust was accompanied by a decrease in B.H.P. of from 1.54 to 1.32, or 14%, and an increase in gas consumption of from 50 to 53 cu. ft. per hr.

Effect of the Knocking Combustion on Thermal Efficiency

Indicated and brake thermal efficiencies based on the lower heating value (L.H.V.) of 424 B.t.u. per cu. ft. at 60° F. and 30 in. of mercury for the town gas are given by the graphs of Fig. 6. The graphs showing efficiencies when

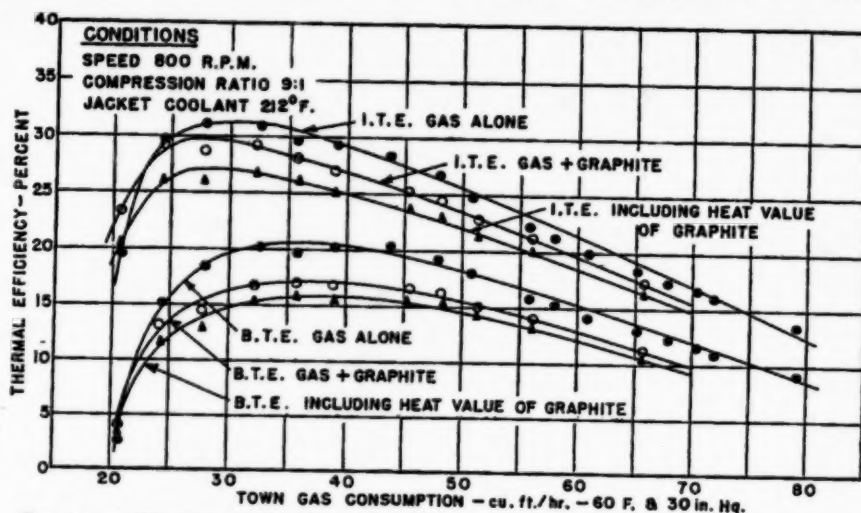


FIG. 6. A-W engine trial; effect of knocking combustion caused by graphite dust to reduce indicated and brake thermal efficiencies.

the heat of combustion of the graphite is taken into account are based on the assumption that it is used with the same thermal efficiency as the town gas. The values shown by the graphs are probably too low because it is doubtful that complete combustion of the graphite occurs when the heat developed can be used with maximum efficiency.

Discussion

It is of interest in respect of the nuclear ignition of gaseous fuels to determine the conditions in which lubricating oil will decompose to the finely divided carbon required to cause the effect.

The absence of finely divided carbon in the combustion space of the A-W engine cannot be attributed to acid-refined oil having been used because a similar result was obtained on using a high grade solvent refined oil or a nonhydrocarbon base synthetic oil for equally long periods of running. It remains, therefore, to consider the combustion conditions in which the finely divided carbon is or is not formed.

When hydrogen alone was used as the fuel for the C.F.R. engine a deposit of fluffy carbon having the appearance of lampblack built up in a few hours

running with the effect of igniting the hydrogen-air mixture; Part V (4). The engine was lubricated with a solvent refined oil.

When town gas alone was used in the C.F.R. engine, the residue from the solvent refined oil was the hard graphitic type of carbon, and nuclear ignition was not obtained even at a compression ratio of 12 : 1, Part XIII (3). When town gas was used alone as the fuel for the A-W engine, there was no residue of finely divided carbon in the combustion space and an almost inappreciable amount of the adherent variety, even after 50 hr. running.

The variable factors affecting combustion in the engines were spark advance and the surface-to-volume ratios of the combustion chambers of the C.F.R. and the A-W engines. The effect of these factors on carbon formation will now be discussed.

Spark advance determines the time of exposure of the oil film on the combustion chamber surface to the destructive effect of flame temperature. The effect over a period of time would result not only in the drastic decomposition of the oil to carbon and hydrogen but in at least partial conversion of the carbon to graphite. When hydrogen was used as the engine fuel, combustion occurred in a few degrees of crank angle and in some cases optimum spark advance was negative, i.e., the mixture with air was ignited after top dead center. It was solely in these combustion conditions that finely divided carbon was found in the combustion chamber.

Combustion conditions were very different when town gas was used as the fuel for the C.F.R. engine. Then optimum spark advance varied from 85 to 15 degrees of crank angle and the oil film was exposed to the destructive effect of the flame for a period many times greater than when hydrogen was used as the fuel. It was in these conditions that the hard adherent graphitic type of carbon was formed.

When the town gas was used in the A-W engine, optimum spark advance varied from 50 to 7 degrees of crank angle and time of exposure of the oil film to flame temperature was approximately half of that in the C.F.R. engine. Furthermore, the relatively large surface-to-volume ratio of the combustion chamber of the A-W engine ensured a lower surface temperature than prevailed in the C.F.R. engine. That is, conditions were such that the lubricating oil could distill off the surface instead of being decomposed to carbon. In any event, conditions in the combustion space of the A-W engine were such that the knocking combustion obtained on adding graphite dust to the gas-air mixture was not caused to any appreciable degree by finely divided carbon derived from pyrolysis of the lubricating oil.

The concentration of 1.5 mgm. of graphite dust per stroke volume shown by the experiments to be required to induce severe knocking in the A-W engine at 9 : 1 compression ratio is equivalent to a concentration of 180 grains per 100 cu. ft. of air at atmospheric pressure. This is a high value

considering that 8 grains per 100 cu. ft. is regarded as a high concentration in a dusty mine (5, p. 1878). It was far in excess of that required for audible knock and was used, as already mentioned, in order to obtain a consequent measurable decrease of power.

The extreme difference between audible knock and the degree used for the experiments, in terms of compression ratio and B.H.P., is illustrated by the graph of Fig. 7, for an experiment with the C.F.R. engine made when

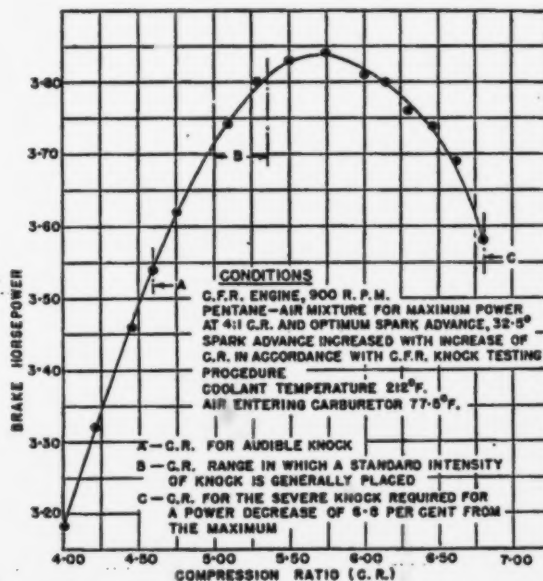


FIG. 7. Graph showing the range of power and compression ratio possible with knock intensity varying from audible to severe.

using *n*-pentane as the fuel. It will be seen that audible knock occurred at a compression ratio of 4.6 : 1; the B.H.P. being then 3.54. The compression ratio could then be raised to 5.27 with a corresponding increase of B.H.P. to 3.8 while the knock intensity did not increase to exceed that commonly used as "standard" and greater intensity could be obtained by raising the compression ratio to 5.62 : 1 before power began to diminish. A still greater knock intensity obtained by raising the compression ratio to 6.8 was required to cause a 9% decrease in power.

Knocking combustion, due to nuclear ignition, requires a suitable concentration of finely divided material in the end gas only. The concentration can be provided accordingly when using hydrocarbon fuels because the decomposition reaction required to provide finely divided carbon can occur preferentially in the end gas in the temperature and pressure conditions

attained late in the combustion period. When, however, a nonknocking fuel such as town gas is used in an engine and the finely divided material added to the gas-air mixture as admitted, it is necessary to impregnate the whole mixture to the concentration required for nuclear ignition of the small part which constitutes the end gas.

It is reasonable to assume that the severe knocking combustion obtained when the gas-air mixture supplied to the A-W engine contained 180 grains of graphite dust per 100 cu. ft. occurred when combustion was 80% complete. The weight of dust in the 20% remaining to constitute the end gas would then be 0.3 mgm. at any one knocking combustion.

There seemed to be a possibility that graphite dust on being added to the gas-air mixture in sufficient concentration to cause severe knocking combustion would give rise to ignition by compression. Special experiments were made accordingly but the effect was not obtained at 9:1 compression ratio; jacket coolant being at 212° F., engine speed 800 r.p.m., and the gas-air mixture supplied at room temperature.

Acknowledgments

The experimental work was carried out with the co-operation of Prof. E. A. Allcut, Head of the Department of Mechanical Engineering, University of Toronto, and Assistant Professor W. A. Wallace. The cost of the work was defrayed in part by an extra mural grant from the Defence Research Board, Canada. The National Research Council contributed to the investigation by lending the Armstrong-Whitworth engine. The Consumers' Gas Company of Toronto contributed by lending a newly calibrated special gas meter and by supplying data for the composition and calorific value of the town gas. The Canadian National Carbon Company contributed by supplying the finely divided graphite.

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